

Review

Accelerating deep-sea research through accessible technologies

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The deep sea is a vast, biodiverse realm that plays a vital role in sustaining life on Earth. After over a century of exploration, however, knowledge of deep-sea processes, lifeforms, and tipping points remains alarmingly shallow. This ‘Perspective’ proposes that maintaining the paradigm of high-cost approaches in deep-sea science, to the exclusion of lower-cost methods, is creating barriers to access and, therefore, progress. Meanwhile, rapid advances in low-cost, open-source hardware, software, and artificial intelligence present an immense opportunity to enable more scalable, inclusive research. Given the ocean’s mounting threats from climate change, biodiversity loss, and resource exploitation, failure to seize this opportunity places our future at risk.

The deep-sea divide

Life on Earth depends on the deep sea. It constitutes an estimated 90% of the planet’s habitable environment and plays a critical role in climate regulation, carbon sequestration, and global food security [1]. Yet, despite the deep sea’s importance, we know very little about it. After a century of dedicated deep-sea research, we have visually observed less than 0.001% of the seafloor [2], mapped less than 30% of the seafloor to biologically relevant resolutions [3], and an estimated million or more deep-sea species remain unknown to science [1].

While the deep sea accounts for the vast majority of the ocean’s volume and hosts great species diversity [4], its researchers comprise only a tiny fraction of the marine research community. Even with commendable efforts to share resources, state-of-the-art research equipment, infrastructure, and software for exploring the deep remain poorly accessible to any but the wealthiest of marine research institutes [5,6]. Limited training opportunities and inconsistent support for low-cost innovations and open-source software further restrict the community that can actively contribute to deep-sea research [7]. This pattern is particularly evident across the North-South divide: developing countries and small island developing states account for three-quarters of the deep sea within national jurisdiction [6], yet are the clear minorities when it comes to research vessel ownership, deep-sea dive operations, and deep-sea research authorship [2,5,8]. Such discrepancies reveal not only the global paucity of professionals trained to study the deep sea but also the vulnerability of developing states and their deep-sea resources to exploitation.

We are in the midst of a global revolution with the power to expand access to technologies and data as never before. Leaps forward in robotics and artificial intelligence (AI) are reducing costs, increasing efficiency, and broadening participation in medicine, manufacturing, transport, drug

Significance

Deep-sea research has historically relied upon specialized technologies that are expensive, complex, and inaccessible to the vast majority of the research community. Recent advancements have the potential to radically reduce costs and increase access to deep-sea research, yet these advancements have not yet spurred a low-cost revolution in deep-sea science. Unraveling the state-of-the-art bias in deep-sea research is essential for greater global equality in science and for understanding deep-sea ecosystems on a timescale that their threats demand.

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development, and aerospace. Lower-cost, open-access alternatives to state-of-the-art tools are increasing access to medical equipment, raising agricultural efficiency, and advancing risk modeling [9]. Deep-sea research is poised for a similar leap forward. It hovers at the cusp of its own revolution. Yet, while so many other industries, sciences, and society at large advance and reap the benefits, deep-sea science has not made the jump. *Why?*

Advances unlocking lower-cost technology and software development in deep-sea research

It is not for lack of ability. Technologies with the power to unlock widespread participation in deep-sea science already exist (Figure 1). Over the last 2 decades, ocean instrumentation has experienced a renaissance driven by inexpensive microcontrollers and computers, open-source software, action cameras, lithium battery technology, and 3D printing. Utilizing these resources, there are numerous examples of robust, low-cost imaging and sensing platforms such as the 'Maka Niu' camera [10], the 'Azor drift-cam' [11], the 'National Geographic DropCam' [12], and other baited remote underwater video systems [13]. Innovations such as the 'PlanktoScope' [14], the 'MARS' auto-release system [15], and low-cost telemetry tags [16] have leveraged these resources to create low-cost alternatives to pelagic microscopy, instrument recovery, and marine megafauna tracking. Cost savings have also been realized with open-source oceanographic sensors [17,18] and 3D printing can now reliably produce custom pressure housings (Motsenbocker, B. *et al.*, 2025, IEEE Oceans Brest, conference).¹ Combined, these innovations can reduce the cost of mesophotic (50–200 m) and deep-sea (>200 m) imaging, sensing, tracking, experimentation, and sample analysis by one to two orders of magnitude: the cost of materials is around \$1000 for the lowest-cost drop camera systems [10,19], \$500 for in-house biotelemetry tags [16], \$150 for programmable automatic release systems [15], and \$1000 for a 'PlanktoScope' [14].¹ Many lower-cost imaging technologies are also smaller and lighter than higher-cost (e.g., remotely operated vehicle (ROV)-based) alternatives, allowing deployments from small research or fishing boats instead of dedicated offshore research vessels, which can bring down daily deployment costs by two orders of magnitude as well [10,11,19,20] (Figure 2).

Such innovations are not exclusive to academia. Lower-cost deep-sea technology is finding success in the commercial sector, with established companies such as Blue Robotics, Lowell Instruments, Blue Trail Engineering, Blueye Robotics, and Sub Sea Sonics. Commercial fishing and monitoring sectors have also developed ropeless fishing systems [21] and environmental sensors [22], further contributing to ocean technology innovation and accessibility.

Simultaneously, open-source and cloud-based software has lowered technical and financial barriers to underwater technology development, mission control, and data processing. Open-source software like 'ROS'ⁱⁱ (Robot Operating System) for robotics, 'MB-System'ⁱⁱⁱ for sonar processing, and 'BlueOS'^{iv} for AUV (autonomous underwater vehicle) control have enabled smaller research centers to independently run their own research missions (Quigley, M. *et al.*, 2009, ICRA workshop). Many of these tools are cloud-based, which allows researchers with limited local computing power and storage to perform complex modeling, mission planning, and autonomous control. Simulators and digital twins are also enabling risk-free prototyping and training in various engineering realms, reducing the need for expensive deployments, accelerating development cycles, and facilitating international collaborations; these systems are in the early stages of development for ocean technologies [23]. Advances in machine learning

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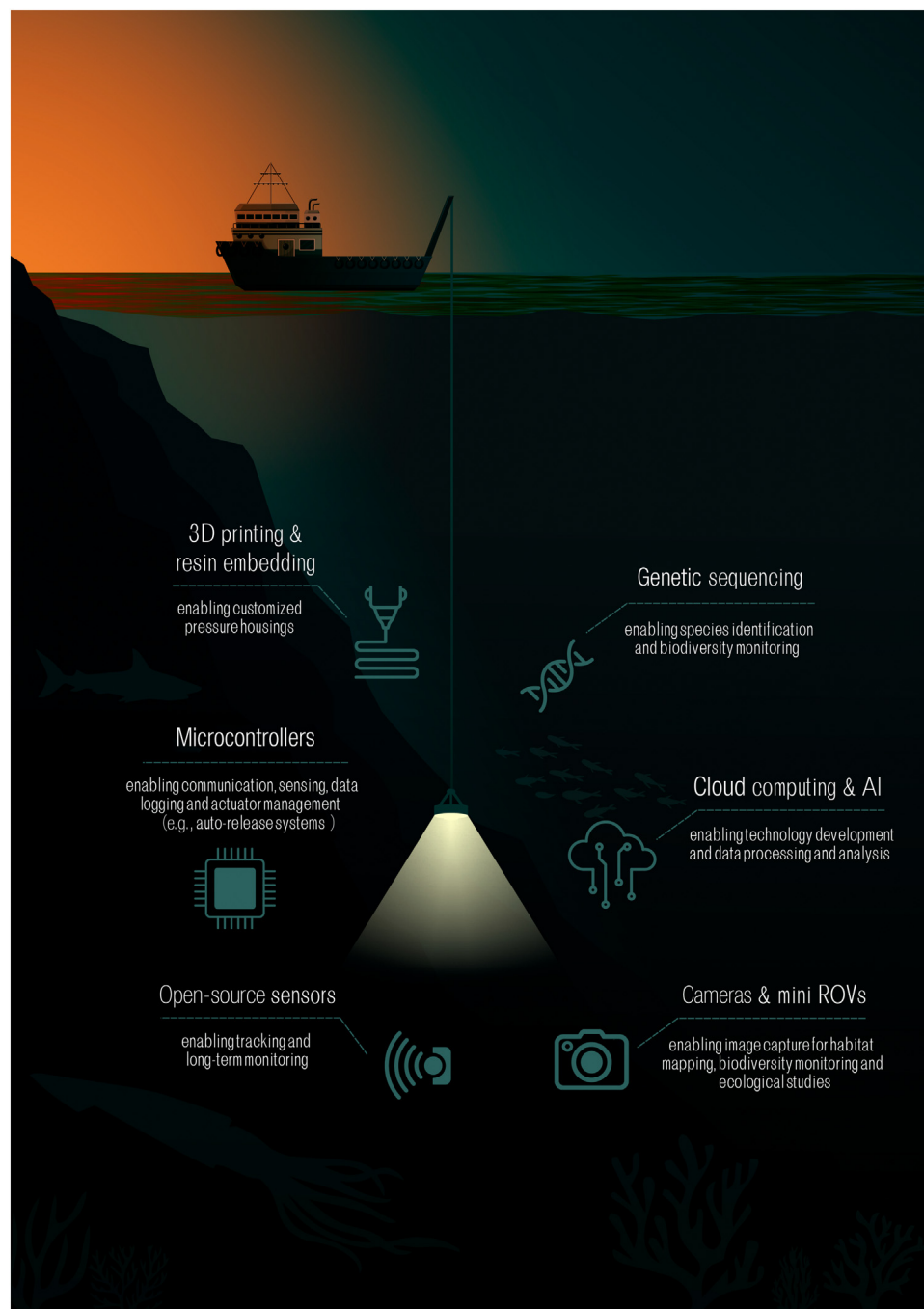
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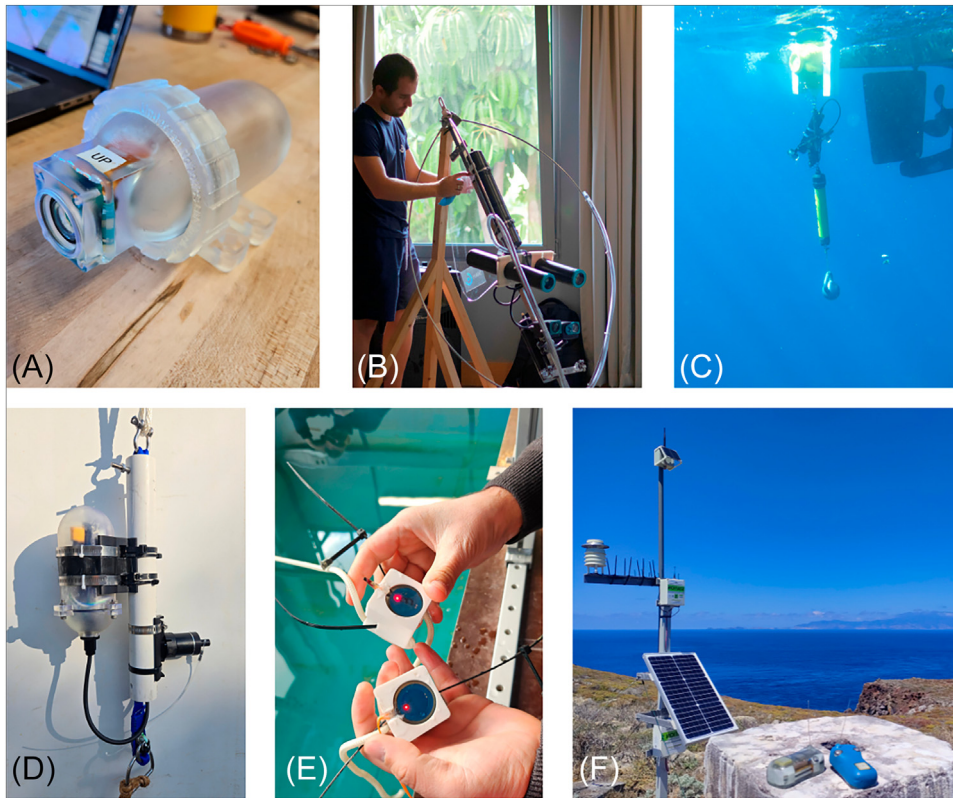
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¹ Often, the deeper the depth rating, the higher the cost. The 'Azor drift-cam', for example, is rated to 1000 m and costs approximately \$20,000. This is still around two orders of magnitude lower in cost than a state-of-the-art ROV used for high-resolution visual surveys at the same depth [20].



Trends Open

Figure 1. Technological advances poised to revolutionize deep-sea research. Reduced costs and greater reliability within microcontrollers, 3D printing, resin embedding, open-source sensors, cameras, miniature ROVs (remotely operated vehicles), genetic sequencing, cloud computing, and AI are facilitating innovations within deep-sea mapping, sensing, monitoring, and data analysis. These innovations can reduce the standard cost of deep-sea research by two orders of magnitude. When deployed from small research boats instead of off-shore research vessels, costs of deployment can fall by another two orders of magnitude. These innovations have the potential to increase global participation in this field, accelerating understanding of deep-sea ecosystems and emerging threats. AI: artificial intelligence.



Trends Open

Figure 2. Low-cost innovations already advancing deep-sea research. Lower-cost alternatives to state-of-the-art deep-sea research tools are already under development and being deployed, expanding participation in deep-sea science and broadening deep-sea datasets. Examples include: (A) a 3D-printed deep-sea housing with an integrated epoxy-potted 'DEEPI' camera on the endcap [13]; (B) an 'Azor drift-cam' [11]; (C) a deep-sea BRUV system (photo courtesy of Kaitlin Noyes); (D) an open-source, deep-sea timed weight release system using an integrated 3D-printed housing for the battery and control electronics (Motsenbocker, B. *et al.*, 2025, IEEE Oceans Brest, conference); (E) the 'MARS' programmable, multi-purpose automatic release system [15]; and (F) low-cost biotelemetry tags and receiver [16].

(ML) and AI are likewise reducing the cost, time, and expertise required to analyze and interpret complex datasets. Today, there are various open-source models automating image, video and acoustic analysis, species classification,^v and anomaly detection [24–26], with 'FathomNet' being a leading example of the power of institutionally led, AI-supported, and community-driven deep-sea imagery annotation [27]. Not only do such models pave the way for any researcher of any financial means to extract meaningful insights from data, but they also facilitate public participation in and understanding of marine science.

Thus, for a fraction of the cost of state-of-the-art equipment and for a fraction of the infrastructure and human resourcing required, a small but growing body of researchers is demonstrating it is possible to explore, monitor and analyze mesophotic and deep-sea ecosystems with lower-cost and open-source tools [10–22] (Motsenbocker, B. *et al.*, 2025, IEEE Oceans Brest, conference).ⁱ Even accepting compromises in data quality and precision, and therefore different use cases, these innovations have the power to radically change the way deep-sea research is conducted today and enable more equitable, broad-based participation.

Roadblocks to further development and widespread use of lower-cost alternatives

Despite the variety of lower-cost alternatives already in existence, deep-sea research is a long way from embracing accessible methodologies. One reason for this may be inertia. Deep-sea research operates with infrastructure that has billions of dollars and over a century of momentum behind it. Historically, high-cost approaches were the only way to explore such a remote and challenging environment as the deep sea, often placing human lives on the line. Understandably, then, deep-sea methodologies have cultivated an aversion to risk that is both something to celebrate (no lives have been lost in the thousands of manned submersible dives undertaken for deep-sea research since 1973, to the authors' knowledge) as well as something to overcome.

A hesitancy to experiment with low-cost options when high-cost, dependable equipment is already in place may be one reason accessible alternatives struggle to gain traction, but it is not the only one. The reality is that many low-cost deep-sea technologies enjoy far lower visibility than their state-of-the-art counterparts and suffer from insufficient lifetime support. This highlights biases within our funding streams, institutions, and even our recognition of success. For example, our academic 'publish or perish' culture pressures scientists to seek rapid results, which favors buying off-the-shelf technology whenever possible [28]. In contrast, many low-cost technology developments operate on project timelines of 3–5 years; not only is this painfully slow compared to purchasing ready-made equipment, but even this is rarely enough time to fully iterate on a technology [29]. Understandably, well-funded institutions and projects often choose the fastest, most reliable ways to access the deep sea, reinforcing a cycle of visibility and output, while low-cost innovations from students and smaller institutes are more often relegated to a purgatory of prototyping and unrealized potential.

A similar dynamic exists within accessible software development. Mature, high-impact, open-source, and/or citizen science platforms are often seen as 'free' to users, but research-ready, professional-quality software requires professional-level maintenance [27,30–32]. Unfortunately, and despite the potential of open-source software to transform deep-sea technology development, operations, and data analysis for the entire community, funders and institutions providing long-term support for these platforms appear to be in the minority. Just as the low-cost technology prototypes that sit on a shelf after a project has ended, open-source data analysis platforms risk becoming obsolete without dedicated backend support.

There are commendable, concerted efforts to share state-of-the-art resources across the deep-sea research community. Some institutes and organizations with access to open-ocean vessels, ROVs, AUVs, and other deep-sea observing infrastructure welcome researchers and students from regions and research centers without access to such tools to participate in their studies and expeditions [5,6,33].^{vi} Some expeditions, like those by One Ocean and COBRA, are even wholly dedicated to training [34].^{vii,viii} These initiatives bring great value not only in the sharing of equipment and data but in the fostering of international collaborations. This 'Perspective' does not diminish the value of such endeavors. Yet, considering their expense and inherent limitations to participation and growth [5,7], it is the opinion of the authors that the deep-sea research community can and should expand the paradigm of deep-sea research beyond state-of-the-art methods. There is much to be gained by fully integrating lower-cost tools and open-source innovations in this esoteric realm.

Benefits of championing lower-cost technology and open-source platform development

How much knowledge could be gained, and how many innovations could be inspired, if deep-sea research were not the privilege of a few but a science of the many? Dedicating more resources to

the development and maintenance of accessible deep-sea technologies has the power to radically increase participation in deep-sea science and strengthen its community across generations, countries, and the global North-South divide. Imagine: the lower the cost of deep-sea technologies, the more deployments across more geographies can be made, the more extreme depths and locations can be studied, and the more students and early-career researchers can receive hands-on training. Reducing the financial risks of deep-sea research not only increases the breadth and depth of our ocean data but also fosters a larger talent pool of researchers and engineers [7]. This, in turn, strengthens the resilience and scalability of these programs and builds a more inclusive and sustainable deep-sea research community.

Early examples of the impact of lower-cost technologies in deep-sea research can already be seen. In the Azores, the ‘Azor drift-cam’ has allowed local researchers to lead the vast majority of deep-sea habitat mapping campaigns in recent years, capturing over 1000 video transects and enabling biodiversity assessments across hundreds of kilometers of the region’s seafloor. The results of this campaign have facilitated science-led marine spatial planning in the Azores, the creation of the North Atlantic’s largest network of marine protected areas, and the design of state-of-the-art expeditions with partners for in-depth follow-up campaigns. All of this was achieved using only 1 % of the cost of traditional, expedition-based habitat mapping methods [20].

The benefits of long-term ocean monitoring and open-access data are also made clear with examples like ‘Argo’. The international ‘Argo Program’, part of the Global Ocean Observing System, supports a vast network of free-drifting, autonomous floats that travel between the surface and 2000 m in depth to collect vertical profiles of temperature, salinity, and pressure in the ocean. Together, a global array of 3000 floats collects 100 000 vertical profiles a year; since its inception in 1999, the ‘Argo Program’ has gathered over three million of these profiles. This program has radically changed *in situ* ocean observation and its data, all publicly available, is utilized by scientists around the world to understand ocean circulation patterns, monitor temperature changes, and make weather and climate forecasts. In its first 20 years alone, the ‘Argo Program’ and its data contributed to over 4000 scientific papers and 250 PhD theses, and these numbers continue to grow [35,36]. Whether or not ‘Argo’ can be described as ‘low-cost’ (each float costs ~\$50 000 to purchase, deploy, and maintain), this program clearly demonstrates the benefits of longitudinal monitoring, large deployments, and real-time, open data sharing to ocean science.

Lower-cost and open-access methods promise a future of richer datasets in deep-sea science, with more baseline surveys and longitudinal monitoring datasets that can complement high-quality datasets from state-of-the-art methods. Even using conventional data analysis methods, such insights will be invaluable to our understanding of the deep sea. In an age where we are just beginning to glimpse the immense potential of ML and AI, however, the power of such large, open datasets cannot be underestimated. Today, the bulk of marine science data annotation and analysis continues to be accomplished manually by students, early-career researchers, and millions of man-hours, making the process slow and costly [27,30,32]. The advent of ML and AI provides the opportunity to greatly reduce workloads, labor requirements, and costs, as already witnessed in areas such as medical imagery, precision agriculture, and ornithology^{ix} [9,32,37]. Realizing this AI-assisted future for the deep sea will require enormous datasets, as well as open-access, easy-to-use data sharing and annotation platforms to train its models, which require human capital to maintain and modernize [30,31]. Although great progress has been made in deep-sea data sharing thanks to platforms such as the ‘Ocean Biogeographic Information System (OBIS)’ and the ‘European Marine Observation and Data Network (EMODnet)’, large amounts of deep-sea data remain poorly accessible or poorly labeled [2,38]

and the training of data annotation models suffers from insufficient available data [27,30,32]. As such, it is the combination of broader participation, data sharing, and support for ML- and AI-assisted data annotation platforms that can truly revolutionize deep-sea science.

The benefit of accessible deep-sea research goes well beyond science and technological development. The integration of low-cost tools in deep-sea science is also a strategic investment toward many of our global development goals. Today, the continued concentration of research efforts in a few wealthy institutions and nations in the Global North [6] not only hinders other communities from studying and managing habitats in their own waters but also undermines ocean stewardship, perpetuates academic inequalities such as authorship bias, and limits the participation of developing economies in global ocean governance [6,39]. Open-source and lower-cost technological innovations, when combined with sustained capacity-sharing and the active involvement of local communities, can unlock a future of more sustainable marine resource management around the world and greater academic equality across the North-South divide [5, 6,20].

Concluding remarks

Deep-sea science faces a critical inflection point. While advances in materials, hardware, and computing are revolutionizing industries and science globally, deep-sea research has yet to unlock their potential to a meaningful degree. Creative low-cost alternatives are emerging [10–22] (Motsenbocker, B. *et al.*, 2025, IEEE Oceans Brest, Conference) and international collaborations are fostering training, discussion, and action to create a more inclusive deep-sea research community [40,41]. However, the field has yet to scale these efforts into a robust deep-sea research network that is accessible, open, and large enough to keep pace with the ocean's ever-evolving threats (see Outstanding questions).

This 'Perspective' proposes a three-step framework to more widely integrate accessible tools and methodologies into the deep-sea research community, with the goal of transitioning deep-sea research from an era of exclusive access to one of distributed global participation:

Step one: Acknowledge the complementarity of lower-cost and state-of-the-art methods. Embracing more accessible tools does not mean discarding existing infrastructure and technologies, but rather working side-by-side to improve outcomes for the field as a whole. Low-cost technology development stands to benefit from state-of-the-art facilities and infrastructure; for example, the pressure testing of low-cost technologies is greatly improved with access to hydrostatic chambers [13] and side-by-side deployments of low-cost and state-of-the-art technologies aid data quality calibration [10]. State-of-the-art campaigns, meanwhile, can be more targeted and efficient following low-cost surveys [20]. Through collaboration, both approaches can achieve greater success and gain numerous efficiencies than when operating in isolation.

Step two: Integrate lower-cost tools into existing capacity-building frameworks and research stays. Today, capacity-building and training programs for deep-sea research often leverage expeditions as opportunities to share methodologies across research centers and regions [6,33,34].^{vi,vii,viii} However, if all the methodologies used in these programs depend upon state-of-the-art infrastructure and technologies, lessons learned may not be readily applicable to building or strengthening local research programs. Instead, if expeditions deploy low-cost alternatives alongside standard technologies, they can create a cascade whereby local programs are able to maintain research efforts long after the expedition ends. Similarly, expanding the possibilities of deep-sea research from being primarily expedition-based to incorporating land-based

Outstanding questions

How can we monitor global progress in deep-sea research accessibility?

How do we rethink academic incentives to reward investment in low-cost innovations?

How do we incentivize timely sharing of labeled deep-sea data to aid machine learning and AI program development?

To better align government and philanthropic support, can we calculate the long-term value of deep-sea research programs for protecting resource sovereignty?

research stays, which depend upon local infrastructure to access deep waters, may further disseminate lower-cost research methods, strengthen international collaboration, and foster the development of more sustainable, self-supporting deep-sea research programs in these locations.

Step three: Better incentivize real-time or near-real-time sharing of data from deep-sea research. Such incentivization may include clearer requirements from funding bodies regarding timely, open-access sharing of deep-sea data and the allocation of a portion of overheads to support long-term open data management. The latter may help ensure adequate support is allocated to platform maintenance and usability, and both can help foster community involvement in data processing and analysis. Important steps toward this future have already been realized in oceanographic data through the 'Argo Program' [35], in deep-sea imagery data through 'FathomNet' [27], and in passive acoustic monitoring data through the NOAA National Centers for Environmental Information archive [31], but large gaps in data access and annotation remain, creating a need for well-maintained global reference libraries, data repositories, and annotation platforms that are accessible to all [30,42].

The deep-sea research community has an immense opportunity ahead to embrace lower-cost, accessible methods, complementing existing capabilities to broaden global participation, enrich datasets, and increase efficiency. Choices made today hold implications not only for the speed of scientific progress in a realm threatened by commercial interests but also for the economic outcomes of vulnerable communities. New institutional, governmental, or private support for lower-cost technology development and open-source platforms is essential for reducing barriers to deep-sea research; for fostering equality within ocean knowledge, governance, and resource access; and for advancing data collection, data sharing, and analysis for the benefit of all.

Author contributions

Conceptualization: J.Di., D.E., and J.C-C. Writing original draft: D.E., J.Di., B.P., J.N.O., R.K-V., M.M.Z., I.A., T.R., R.F., M.Pi., M.Pr., J.Du., D.V., J.P., J.G.M., and J.C-C. Review and editing: D.E., J.Di., B.P., J.N.O., R.K-V., M.M.Z., I.A., T.R., R.F., M.Pi., M.Pr., J.G.M., J.C-C., M.R., H.S., J.Du., D.V., J.P., B.M., P.D.L.T., V.K., F.V., F.A., and S.S. Visualization: J.C-C., D.E., D.V., P.N., F.A., B.P., and M.Pi. All authors have read and approved the final manuscript.

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Resources

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